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FALSE SPECTRA FROM THE ROWLAND CONCAVE GRATING.

BY THEODORE LYMAN.

Presented October 10, 1900, by W. C. Sabine. Received October 26, 1900.

IT is proposed to show in the following paper that among the spectra formed by the Rowland concave gratings there are spectra not accounted for by the ordinary theory of the grating; that such spectra are common, and at times fairly strong and of excellent definition; that these spectra are diffraction spectra, of much less dispersion than the ordinarily recognized spectra, and that the errors of ruling to which they are due are not local, but general to the whole surface of the grating. Finally, it is proposed to explain an experimental method by which these false lines can be sorted out from the regular and calculable overlapping spectra. These lines are especially dangerous in series spectra work, giving a somewhat systematic reproduction of strong lines and groups, which reproductions in actual vibration frequencies do not exist. There is probability and some evidence that such errors have been committed in the past, and it was in the presence of this danger that the false spectra were here discovered.

In the year 1893, Schumann showed that the ultra-violet spectrum could be extended to the neighborhood of 1000 μ. He used a spectroscope fitted with a fluorite prism and fluorite lenses. The apparatus was so constructed that it could be enclosed in a case from which the air could be exhausted. According to his investigation, it was chiefly the absorption of the air for light of very short wave lengths that had prevented other investigators from extending the spectrum below wave length 1800 μ. Owing to the nature of a prism spectrum, it was difficult for Schumann to determine accurately the wave lengths of the lines which he discovered. Since his paper no attempt seems to have been made to measure these lines. It was in an effort to measure these wave lengths that the false spectra above referred to were first observed.

It seemed probable that if a concave grating could be used to obtain these ultra-violet lines, an accurate determination of their wave length would be possible. Accordingly, some two years ago, Mr. E. H. Colpitts and the writer undertook the investigation. The methods used and the results obtained were briefly as follows: —

The concave diffraction grating, slit, and photographic plate were all enclosed in an air-tight cast-iron box. Light was admitted to the box through a fluorite window. The source of light was a powerful electric spark, obtained from a transformer run from the commercial circuit; a capacity equivalent to four large Leyden jars was placed in parallel with the spark gap; magnesium was used for terminals. Following Schumann's work, the air was exhausted from the box. The spark was placed close to the fluorite window in order that the column of air between the source and the plate should be as short as possible. Under these circumstances a photograph was obtained showing lines apparently down to wave length $924\,\mu$, a value lower than Schumann's lowest estimated wave length. Terminals of aluminum, cadmium, cobalt, nickel, and copper were tried. All showed lines below $1500\,\mu$; some showed lines as far down as position $950\,\mu$.

During these experiments, the air pressure in the apparatus did not always have the same value. Some plates were taken with the pressure as high as 1 cm.; others with it as low as .2 cm. It was observed that this difference in pressure did not have any effect on the strength of the lines.

Up to this time the first spectrum had been used; now it was desired to find these lines in the second spectrum. In spite of the greatest care, however, no trace of any line below $1900\,\mu$ could be found in the second spectrum.

The absence of the lines in the second spectrum, together with their behavior under small differences of air pressure, raised the suspicion that either the lines were not due to light of a very small wave length, or that light of very short wave length was not absorbed by the air to the extent indicated by Schumann. To test this idea the spark was first removed to a metre's distance from the fluorite window. This air column did not reduce the intensity of these new lines. Next, air was admitted to the box, and still the lines were unchanged in intensity, even through a column of air, now five metres long. Evidently the lines were not absorbed by air.

Lest the special brand of plate employed was particularly sensitive to the extreme ultra-violet, a number of different plates were tried. In each case a good photograph was obtained, showing practically all the lines.

A piece of window-glass was placed between the slit and spark, and no trace of the lines could then be found. Since the light causing these lines is absorbed by glass, and is not absorbed by air, it would seem to have a wave length between 3500 μ and 2000 μ, according to the accepted absorbing power of these two media.

It was now observed that the groups at 2790 μ, 1873 μ, and 924 μ were, even to casual inspection, strikingly characteristic and identical in general appearance. Further, on measuring their dispersions, they were found to be proportional to the displacements of the groups from the slit. Therefore, these groups formed either a remarkable series reproduction or a heretofore unobserved diffraction phenomenon. Thus the issue was definitely raised whether these lines were real first spectrum lines, produced by light of wave lengths 924 μ, 1873 μ, and 2790 μ, and arranged in a 1, 2, 3 series, or whether they were all produced by light of one wave length and owed their position to some diffraction phenomenon connected with the grating.

To distinguish between these alternatives, recourse was had to the relative refrangibility of these lines through quartz. To this end a small angle quartz prism was placed between slit and grating and a short distance from the slit. The effect of this prism was to produce virtual images of the slit whose displacements were nearly proportional to the refrangibility of the light. This device resulted in the displacement of each line in the grating spectra by an amount proportional to the refrangibility of the light producing that line.

If the lines at 1873 μ and 924 μ were caused by light of the same wave length, they would suffer equal displacements. If they were caused by light of different wave lengths, they would be displaced by different amounts.

The experiment was tried, and it was found that the groups at 2790 μ, 1873 μ, and 924 μ all suffered about equal displacements. From 2790 μ down to the region of 1873 μ, the displacement of the groups increased as the wave length decreased. There was then a discontinuity in the rate of increase of the displacement before 1873 μ and a second discontinuity between 1873 μ and 924 μ.

The most obvious conclusion from these data is that the lines at 1873 μ and 924 μ are not due to light of wave lengths corresponding to the positions of the lines in the spectrum. They seem to be caused by light having a wave length near 2800 μ; they seem to be reproductions of some part of the true spectrum, — curious phantom lines due to some property or imperfection of the grating. An examination of the lines below 1900 μ taken with aluminum terminals fully carried out this theory. Before leaving this first grating, which we will call No. 1, it is important to note that although the groups in magnesium at 2790 μ, 1873 μ, and 924 μ closely resemble each other, their wave lengths are not exactly in the 1 : 2 : 3 ratio; 2 × 924 = 1848, which differs from 1873 by 25.

It was proved that these phantom lines were not due to any local variation in ruling by shielding all but a narrow strip of grating surface, and then moving the screen so as to expose each strip in turn. In this way a series of photographs were obtained, each from a different strip of grating surface. They all showed the phantom lines with about equal intensity.

In addition to the grating with which the investigation was begun, three others were examined. Two of these were of larger radius, — 21 ft.; the other was similar in type to the first instrument. Of the two large gratings, one showed the phantom lines distinctly. The two strong groups formerly at 1873 μ and 924 μ were now found at positions corresponding to 1728 μ and 1079 μ. The other large grating did not show the lines at all. The last small grating showed the reproduction of group 2790 μ at positions of about 1870 μ and 924 μ. In addition, however, there were also numerous less distinct reproductions scattered between these two positions.

We may now sum up the facts arrived at in these few pages. Of four concave diffraction gratings examined in this investigation, three showed the phenomenon of phantom lines. These lines vary in position with the grating by which they are produced, but the variation cannot be connected either with the variation of radius of curvature of the grating or with the number of lines to the inch. The most prominent of these phantom lines closely resemble some group in the true spectrum. This repetition of a true group occurs most strongly twice. The width of these phantom repetitions is proportional to their apparent wave length. The wave lengths of the true group and its phantom repetitions bear no simple relation to one another. The photographs obtained with gratings 1 and 4 show a very large number of faint repetitions of a group or set of groups. These repetitions form a sort of background to the main spectrum between 1800 μ and 900 μ.

It may be safely said that a strong line in the spectrum is repeated a great number of times, and that these phantoms are distributed apparently at random. We have no reason to believe that this repetition is confined to a certain proportion of the ultra-violet spectrum. Every line in the spectrum is probably reproduced. These reproductions are concealed by the strong real lines of the spectrum in places where strong lines occur. They are chiefly noticeable in the extreme ultra-violet, where there are no real lines. In parts of the spectrum where gaps occur, however, these phantoms may be visible and may there be mistaken for real lines. Such, in brief, are the results arrived at. A more detailed account of the apparatus and of the numerical results of the investigation will now be given. The consideration of the causes which produce these phantom lines is left for the end of the paper.

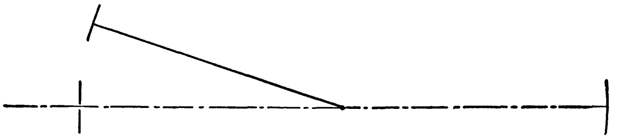


FIGURE 1.

The first grating investigated was one of 180 cm. radius. The plate was prepared by Brashear and ruled by Rowland's engine in the year 1897; it had 14,438 lines to the inch. To economize space a mounting somewhat different from that of Rowland was used. The grating and slit were fixed in position at a distance apart equal to the radius of curvature of the grating. The plate-holder was carried by an arm pivoted at a point on the line connecting slit and grating and midway between the two. The length of the arm was, of course, half the radius of the grating. The plane of the grating was so adjusted that the principal image fell about 1 cm. to the right of the slit. This was done to avoid reflection from the polished jaws of the slit. The plate-holder was constructed to take a plate five inches long and one inch broad. The form of the box in which the apparatus was enclosed is not material to this investigation. The spark which served as a source of light was placed within 3 mm. of the fluorite window. In the first experiments the width of the slit was about .1 mm., and the time of exposure was about one hour. Later, however, good photographs were obtained with exposures of from twelve to fifteen minutes. In making tests for the absorption of the air a quartz lens was placed between the source and the slit.

In developing photographs of this type, great contrast is the chief object. The kind of developer used thus becomes important. After several trials, an Ortol-Soda developer was found to give the best results.

The apparent wave lengths of the different lines which come under consideration were determined by comparison with the normal sun spectrum. A dividing engine with a $\frac{1}{2}$ mm. screw was used. This screw, when used to measure lines on a six-foot grating possesses for a run of 20 cm. an accuracy better than one one-hundredth of an Ångström unit. The plate was observed by means of a stationary microscope fitted with a four-inch objective and micrometer eye-piece. The value of one centimeter of plate length in terms of Ångström units was determined by measurements taken between two given sun lines, located by Rowland's map. In order to get a photograph of the sun spectrum and the magnesium spectrum on the same plate, a shutter was placed before the slit and so adjusted that the upper or lower half could be exposed at pleasure. By this means two narrow spectra were obtained, one above the other. The method is preferable, when working with the first spectrum, to the usual mode of protecting the plate itself by a swinging screen.

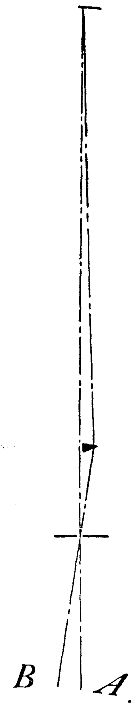


FIGURE 2.

When it became necessary to test the nature of the light producing the lines at 1873 μ and 924 μ in the magnesium spectrum, the following arrangement was adopted: The quartz prism of an angle of five degrees was placed some 30 cm. distant from the slit, but not on the straight line joining slit and grating. Thus when the source was in position A, the light did not fall upon the prism; but when it was in position B, the light passed through the prism. In the first case, the upper half of the slit was closed by the shutter; in the second, the lower half was closed. The result was, of course, to produce two spectra, one above the other; the one due to light which had passed through the prism was thus shifted toward the red. The general appearance may be seen from Plate No. I.

It now becomes necessary to consider more in detail the behavior of the light of these ultra-violet spectra when passed through the quartz prism. The results for magnesium may be seen from the following table. The lettering of the groups on the plans of the spectra is, of course, arbitrary. The chief or real groups are marked with an unsubscripted letter. The reproductions are marked with letters bearing a subscript. The plates are from drawings made from the original photographs. Beginning with magnesium Plate II., six principal groups of lines are to be noted; they extend from the pair of lines marked A_1, — wave length 1966 μ, — to the strong group C_4, — wave length 924 μ. Besides these strong lines, there are six fainter groups distinctly visible, — A_2, b_1, C_2, A_3, b_2, and C_3. A_2 resembles group A_1, C_2 group C_1; C_3 resembles group C_4, A_3 group A_4. It is to be noted that while A_2 and C_2 lie on the right or ultra-violet side of A_1 and C_1, C_3 and A_3 lie on the left or red side of C_4 and A_4. In addition to the simple groups of lines already mentioned, the whole spectrum, from one end to the other between A_1 and C_4, is filled with a number of fine, faint lines. These lines are not regularly arranged so as to produce fluting, but rather present the appearance of a reproduction of groups of lines.

MAGNESIUM.

Group.	Apparent wave length.	Displacement.
C	2790 μ	42.2 mm.
I	2713 μ	43.4 mm.
II	2682 μ	43.9 mm.
A_1	1966 μ	42.1 mm.
A_2	1924 μ	
b_1	1914 μ	
C_1	1873 μ	42.2 mm.
C_2	1834 μ	42.3 mm.
D_2	1475 μ	39.8 mm.
E_2	1266 μ	40.2 mm.
A_4	969 μ	41.9 mm.
C_3	964 μ	
b_2	944 μ	
C_4	924 μ	42.2 mm.

ALUMINUM.

Group.	Apparent wave length.	Displacement.
I	2376 μ	38.8 mm.
B_1	2075 μ	36.1 mm.
C_1	1890 μ	36.7 mm.
D_2	1300 μ	34.9 mm.
E_2	1184 μ	35.3 mm.
B_3	1023 μ	36.0 mm.
C_3	933 μ	36.6 mm.

If we examine the displacements produced in these groups when the light is allowed to pass through the quartz prism before falling upon the grating, the following facts become evident: A steady increase in displacement is observed in the successive lines going from the strong group at 2790 (C) towards the ultra-violet until we get in the neighborhood of group A_1. At this point the amount of displacement suddenly returns to about the value it had at 2790 μ. Between groups A_1 and D_2 the displacement suffers a second discontinuity. Thus A_1 gives 42.1 mm., D_2 39.8 mm. The displacement of C_4 is almost exactly that of C_1, and very nearly that of group C, — 2790 μ. The figures are 42.25 mm., 42.25 mm., 42.21 mm. As stated before, the most obvious conclusion from these data is that the lines A_1 to C_4 are not due to light of wave lengths corresponding to the positions of the lines in the spectrum. They seem to be reproductions of some part of the true spectrum.

On the aluminum plate there are present six strong lines, — B_1, C_1, D_2, E_2, B_3, C_3, — with wave lengths from 2075 μ to 933 μ. There are faint reproductions of these groups similar in arrangement to those observed with magnesium. There is a background of fine, indistinct lines. On allowing the groups to be displaced by the prism, we find group D_2 less displaced than group C_1, and group B_1 less displaced than a real group called I.

We may now consider the false nature of the lines as established. It remains to investigate the causes which produce this diffraction phenomenon.

It is perfectly evident that the phantoms are not due to a local variation in the rate of ruling, such as produce ghosts; for we have seen that the fault is not local in the grating surface. Moreover, we know that a ghost always occurs close to the line of which it is a reproduction.

The phantoms are not due to a false source of light, since the dispersion of the various reproductions is not the same as that of the real group. We may discard the hypothesis that the mounting of the grating or the position of the source of light has any effect. The lines occur with various forms of mounting and with various positions of lens and source, as will be seen later. We have to deal with a diffraction phenomenon, with an inherent property of the diffraction grating itself.

It seems probable that in developing the theory of the grating some assumptions have been made which are not according to fact. It is in the error of such assumptions that we find the solution of our problem.

It is generally assumed in treating the grating that the lines of the ruling are of equal width and are separated by equal spaces. In the very nature of things, it is evident that this cannot be the case in view of the very minute distances involved and the almost inconceivable rigidity which would be necessary. These variations, slight in absolute amount, may be a considerable fraction of the distance from line to line. It is clear, moreover, on experimental as well as on theoretical ground, that these variations are not local, but extend over the whole surface of the grating.

It appears, then, that the departure from equal spacing assumed in the theory of the concave grating is not the random departure which is next in theoretical simplicity, but a more or less systematic departure which has emphasized disproportionately certain of the subordinate maxima called for in the conventional theory. If the position of the false maxima occurred in the ratio 1 : 2 : 3, or in any other simple ratio, the phenomena would invite an analytic discussion. As an experimental fact, however, our lines are not harmoniously placed with respect to the slit, nor are they arranged according to any discoverable system. Moreover, they are different in character and position when obtained by different gratings ruled by the same engine. It seems most likely that the phantom lines are due to a number of superposed first spectra of varying dispersions; and that these false spectra owe their existence in some manner to the variation in width and separation of the grating lines. Under these conditions, an analytic discussion seems less profitable than the presentation of the experimental data.

In order to substantiate the statements just made, it becomes the next object of the investigation to observe carefully the relative positions of the phantom lines, not only in one, but in several different gratings.

We must observe, in looking over the tables already given, that although several groups bear a strong resemblance to each other, and though the apparent wave lengths of these groups are nearly in one, two, three ratio, this ratio is never exact.

In aluminum, the line C_3 seems to resemble the line C_1, but $2 \times 933 = 1866$, not 1890. The group B_3 resembles B_1, but $2B_3 = 2046$, not 2075. There certainly is no exact 1, 2, 3 relation, although lines corresponding roughly to $3C_3$ and $3B_3$ in wave length may be found for aluminum. The difference between 2046 and $2075 = 29$ Ångström units cannot possibly be due to the error of observation. It is perfectly safe to say that the measurements of wave lengths in the table are correct to 1 Ångström unit.

Before examining another grating, there are one or two more points which need attention. A concave grating produces two spectra of the first order, which in this form of mounting lie on each side of the slit. The spectrum on the left had been investigated; it was now necessary to observe the spectrum on the right of the slit. The grating was therefore turned upside down, by which process the spectrum formerly on the right of the slit now fell upon the left. Photographs taken showed the lines A_1, C_1, A_4, C_4, etc., in magnesium as clearly as before. The grating was next turned about a vertical axis until the direct image of the slit fell upon the plate. No lines below group C_4 were revealed by this process, nor was the position of the lines greatly changed. It must be noted, however, that the turning of the grating will somewhat distort the spectra and change the value of μ to cm.

The second grating to be investigated was of 21 ft. radius, 14,438 lines to the inch. It was arranged on Rowland's mounting. The intensity of the spectra given by this grating was very inferior to that obtained with the 6 ft. instrument. The first spectrum was selected to work with, the magnesium spark was used as a source. It was found necessary to give an exposure of an hour, and to use a slit .2 mm. in width. A good deal of care was taken to have the exposure of the proper length; if too short, the lines themselves would not appear; if too long, the lines would be obscured by fog. With this 21 ft. grating, a very little fog would quite shield any very faint line. After some trouble, the characteristic reproductions of group 2790 were found. They now occurred, however, at positions corresponding to wave lengths of 1728 μ, 1079 μ. The widths of the groups were 4.8 mm., 2.8 mm., 1.8 mm. Thus, though these phantom lines have different apparent wave lengths when measured on different gratings, their dispersion seemed proportional to their wave length. It must be noted that with grating No. 2 only the lines called A_1, C_1, and A_4, C_4 are visible, the other fainter lines, as well as the fluted effect in the background, being totally absent. This is well accounted for by the feebleness of the spectrum obtained from grating No. 2. The apparent wave length of these groups was obtained by the same method as that previously employed. Owing to the great distance between the head group (2790) C and its reproductions, a cathetometer was used. The results are correct, however, to better than 2 Ångström units. The widths of the groups were measured on the dividing engine and are correct to within .03 mm. The value of 1 cm. of plate length was obtained from measurements between two sun lines.

I feel certain that groups 2790 μ, C_1 and C_4 as obtained with grating No. 2 are not in 1 : 2 : 3 ratio.

The next grating investigated was one of 21,000 lines to the inch and 21 ft. radius. Here the illumination was even more feeble than with grating No. 2. Great trouble was experienced from fog. The lines in magnesium, C_1 and C_4, could not be found. The last grating examined was similar to No. 1. It had a radius of 183 cm., 14,438 lines to the inch; it was prepared by Brashear; it was ruled by Rowland's engine at

Johns Hopkins in the year 1894. The mounting was the same as that of grating No. 1.

The character of the photographs obtained with grating No. 4 was quite different from those obtained with grating No. 1. Lines A_1, C_1, and A_4, C_4 were present, and with about the same apparent wave length as before. They were, however, very much less distinct than when obtained with grating No. 1. The fluting effect was not very sharp; but, on the other hand, the space between positions $1878\,\mu$ and $924\,\mu$ was filled with reproductions of groups A_1 and C_1, of such clearness as to be quite unmistakable. The wave lengths of some of these phantom lines was determined in the same manner as before. Groups corresponding in appearance to the family marked A_1, A_2, A_3, etc., were found at $1970\,\mu$, $1020\,\mu$, $993\,\mu$, and $970\,\mu$. The groups called C_1, C_2, etc., were found at $1878\,\mu$ and $924\,\mu$ very clearly, and at more than eight other positions in a less distinct form between 1878 and 924. In fact, the spectrum in this region is so filled with groups of the A, C, type that the lines of one family overlap lines of the other in many cases.

Such, then, are the experimental data connected with this phenomenon. Before coming to a statement of conclusions, however, the following facts are of interest: —

Some of the reproductions belonging to the set of lines A_2 and E_2 in aluminum occur under the real spectrum, and may be observed if proper care is used.

Gratings of large radius do not show the false lines with as much clearness as gratings of small radius. So feeble, indeed, are the false lines obtained with the 21 ft. grating, that it is improbable that they would be noticeable in ordinary spectrum work. With a six-foot grating, however, the false lines are so strong that they might easily cause errors in series spectrum investigations. We have seen, moreover, that the false lines from grating No. 1 are much stronger than those from grating No. 4, and we have reason to suspect that gratings exist which produce false lines even stronger in character than those obtained with grating No. 1. Gratings 1 and 4 differ little in radius, and have exactly the same number of lines to the inch, yet their false spectra are entirely different in character. We cannot apparently predict the nature of the false spectra of one grating from the false spectra produced by another of the same ruling and radius.

The conclusions arrived at in this paper may be stated as follows: —

1. The first spectrum produced from the Rowland concave grating is not pure, but is complicated not only by underlying spectra of

higher order, but by the presence of a number of spectra of lower dispersion.

2. The number and dispersion of these false spectra obey no simple law, but present the appearance of a reproduction of some real group or groups distributed at random.

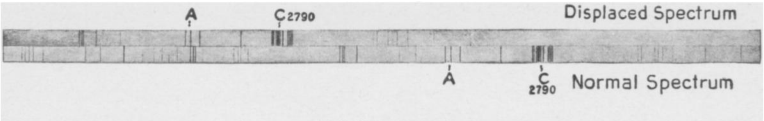
3. The number, dispersion, and clearness of these spectra differ with different gratings.

4. The lines due to the false spectra are most clearly visible in the extreme ultra-violet, owing to the absence of strong real lines, and are so pronounced as to screen any feeble real line that may occur in this region.

Jefferson Physical Laboratory, Harvard University,
Cambridge, Mass., October, 1900.

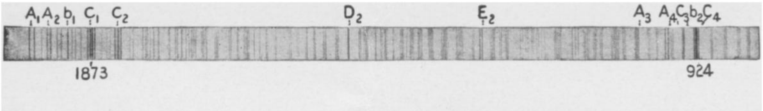
Lyman. — False Spectra.

PLATE I.



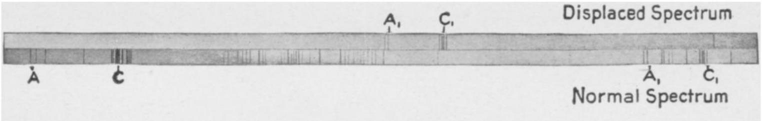
MAGNESIUM

PLATE II.



MAGNESIUM

PLATE III.



MAGNESIUM